The Impact of Mission Duration on a Mars Orbital Mission

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Performance alone is insufficient to assess the total impact of changing mission parameters on a space mission concept, architecture, or campaign; the benefit, cost, and risk must also be understood. This paper examines the impact to benefit, cost, and risk of changing the total mission duration of a human Mars orbital mission. The changes in the sizing of the crew habitat, including consumables and spares, was assessed as a function of duration, including trades of different life support strategies; this was used to assess the impact on transportation system requirements. The impact to benefit is minimal, while the impact on cost is dominated by the increases in transportation costs to achieve shorter total durations. The risk is expected to be reduced by decreasing total mission duration; however, large uncertainty exists around the magnitude of that reduction.

I. Introduction

When developing a space mission concept, architecture, or campaign, there are certain mission parameters (drivers) that, when changed, significantly alter the behavior of the design space with respect to the key decision-making metrics: benefit, cost, and risk. Often, the impact (the effect of changing a mission parameter on decision-making metrics) of these drivers is measured with respect to changes in performance, such as mass or efficiency. However, the total impact (beyond the scope of performance) must be considered to make an informed judgement on the importance or influence of that driver. The total impact is the change in benefit delivered by the mission, the change in cost to perform the mission, and the change in risk to the mission. In this context, the performance of the mission, rather than being the sole decision-making metric, is the mechanism by which the driver is changed to alter the benefit, cost, and risk.

One such driver is the total duration for a human Mars orbital mission. With current technology, transit to and from Mars takes months to years to complete, with stays in the sphere of influence of Mars ranging from a month to five hundred days. Hundreds to thousands of tons of mass must be launched to perform this mission. This behavior of the transportation architecture has implications for the rest of the mission: habitation systems must be designed to support the crew for these long durations away from Earth, systems must be highly reliable and/or reparable, and the required technologies and systems require significant investment. These requirements may be relaxed if the total duration of the mission can be reduced; however, reducing duration carries with it its own set

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of challenges. Thus, a need exists to understand these challenges to determine the value of investing in reducing total mission duration.

This paper assesses the sensitivity of the total impact of a given driver: the impact of changing the total mission duration for a human Mars orbital mission. This paper includes a discussion of the quantitative and qualitative means to assess the three impacts (benefit, cost, and risk) in a human Mars orbital mission. The two performance trades used to achieve lower mission durations are mission design changes and propulsion technology advances. These performance trades on the transportation system, in conjunction with the impact of reduced mission duration on other elements (e.g. the crew habitat), are used to inform the assessment of impacts on benefit, cost, and risk.

II. Background

A human Mars orbital mission is defined here as a mission that sends humans to Mars orbit without going to the surface. This enables missions to Mars before the entry vehicle, surface elements, and ascent vehicle are developed. In Martian orbit, the crew would be able to teleoperate robotics on the surface, observe Mars from orbit, and complete other mission objectives. The crew would live in a deep space habitat in transit to and from Mars, as well as while in orbit. Traditional, high-thrust conjunction class missions have durations in Mars orbit on the order of 500-600 days and transit times up to 250 days each way. Throughout this entire mission, the crew is exposed to deep space radiation and, assuming traditional habitat design, microgravity.

In assessing mission concepts (such as a Mars orbital mission) and informing capability investment choices, systems analysts typically will consider the mass impact of trades such as choosing to perform an orbital mission instead of a surface mission to Mars, or using different propulsion technologies to change transit time. An indicator of this tendency is the prevalent use of Initial Mass in Low Earth Orbit (IMLEO) as a comparison metric [1]. Understanding the impact on mass alone, however, only provides partial knowledge. Other impacts must also be considered when making a decision, such as:

- the added benefit gained during the mission due to the use of a new technology;
- the difference in cost from development, production, launch, and operations of the mission; and
- the difference in risk to the crew or systems due to new operational modes or technologies.

An example of this tendency is represented by historical studies on the benefits of in-situ resource utilization (ISRU) for Mars surface missions. From research into ISRU propellant production studies, Jones (2016) found that previous attempts at determining the degree of savings provided by ISRU propellant concentrate on either reductions in mass on the Mars surface or IMLEO [1]. These studies did not take into account the non-trivial cost to develop and implement the ISRU infrastructure to create that propellant. While some studies in the literature [2,3] have acknowledged this fact, quantitative assessments of the other impacts (benefit, cost, and risk) are an underexplored area of research in ISRU for Mars surface missions. Similarly, the assessment of other metrics besides mass allow for better understanding of the full impact of choices in a trade space.

III. Total Impact of a Mars Orbital Mission

This paper will explore the total impact, including benefit, cost, and risk, of changing the total mission duration of a Mars orbital mission. This analysis will also consider the various propulsion trades available to achieve this reduction in total mission duration. Figure 1 presents an overview of this process. The impacts of the driver, Mars Orbital Total Mission Duration, are on the right while the trades to enable that driver are on the left. This figure also presents the initial findings of the relative importance of each impact and trade which are discussed further in the following section. A major impact or trade is one that has the potential to significantly alter the behavior of a decision (e.g. the impacts of radiation on crew health may determine whether a mission can even be attempted at all). A minor impact or trade is one that on its own does not significantly alter the behavior of a decision, but in conjunction with others may prove significant (e.g. habitat costs on their own do not drive the behavior of cost, but in conjunction with the costs of spares, are on the order of transportation costs for long durations). A minimal impact or trade is one that is unlikely to alter the behavior of a decision, regardless of the value of the driver (e.g. prestige depends only on whether or not the mission is successful; it is unaffected by duration). Validated assessments are based on quantitative analysis presented in this paper; presumed assessments are based on expert solicitation.

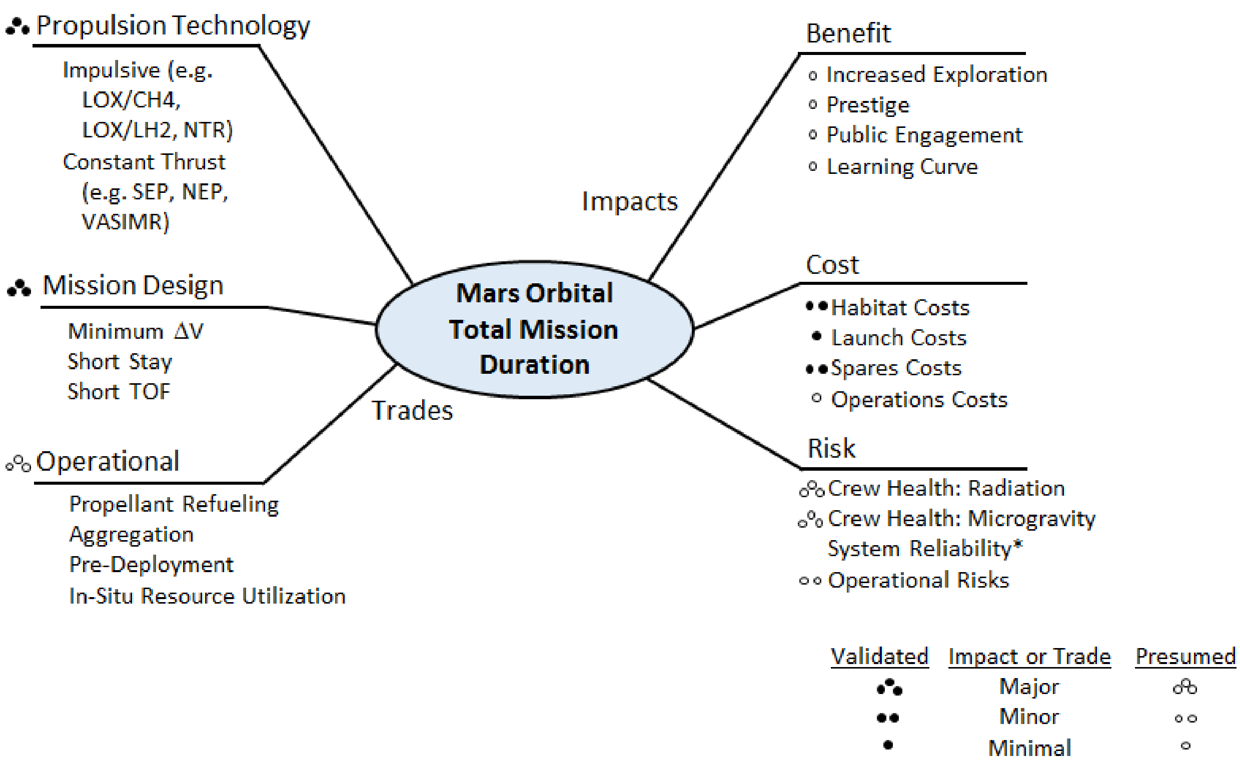

Figure 1: Overview of Process to Assess Total Impact

A. Benefit

Benefit is tied to the "why" of a mission; that is, a mission exists to provide benefit. This paper proposes several components of benefit with respect to a human Mars orbital mission: increased exploration, prestige, public engagement, and increased learning curve. Each of these components was evaluated across a range of mission durations to estimate the magnitude and nature of the change in benefit as a function of mission duration. The four components and their relationship with total mission duration are presented in Table 1. The degree of exploration that can be completed (e.g. via tele-operation of surface assets) in an orbital mission depends on stay time in the Mars vicinity rather than total mission duration. The national prestige of a Mars mission is a binary variable tied to the success or failure of the mission; there is no dependency on either total duration or transit time. Faster pacing between missions increases public engagement and the rate at which lessons learned from previous missions can be applied to subsequent missions; however, this is not solely a function of mission duration, but also depends on opportunities and funding to support those subsequent missions. In summary, decreased total mission duration has minimal impact on benefit for a Mars orbital mission as described here. Other potential benefits not included in this assessment include advances in technology and related spinoffs that may result from shorter or longer mission durations.

Table 1: Overview of the Benefit Impact

Component	Description
Increased Exploration	Benefit increases with stay time (from decreases in transit time combined with fixed total duration) by providing more time for tele-operated surface science.
Prestige	National prestige from being the first to go to Mars has no dependency on total duration or transit time; it only depends on whether the mission is successful.
Public Engagement	Shorter time between publicly interesting events (Earth launch, Mars arrival, Earth return) may increase public support/enthusiasm for mission; interest decreases rapidly between events.
Learning Curve	Shorter total durations may allow for more frequent missions to Mars or spacing between missions, which provides more opportunities to apply lessons-learned to subsequent missions.

B. Cost

The cost impact incorporates the total cost of the campaign including the costs for the habitat (development and production), spares, launch, and operations. Transportation system costs are excluded in this analysis, because they are considered an independent variable that drive the shorter mission durations. The habitat cost and the spares cost are closely tied to the total mission duration, but factors such as life support closure affect the sensitivity of those costs. The launch cost, similarly to the in-space transportation system cost, are more closely tied to the performance trades and thus can vary significantly for different options. The fixed costs for operations are assumed to dominate any dependence on total mission duration, an assumption that needs to be verified with further analysis. Table 2 presents an overview of the components of the cost impact.

Table 2: Overview of the Cost Impact

Component	Description
Habitat Cost	The cost of the habitat system, which includes the structure, life support, power, and other systems, scales to account for varying total mission duration.
Spares Cost	The cost for spare parts to account for system failures, which increases with total mission duration, depends heavily on the life support closure strategy.
Launch Costs	The cost to deliver mass to orbit is modeled as a linear function of mass to be launched.
Operations Costs	Operation of ground systems, flight control, etc. tend to have high fixed costs, which implies weak correlation with mission duration.

Figure 2 presents the habitat mass across a range of total mission duration from a few days to a few years. For the parametric cost estimating methodology employed in this study, the cost of a space system is a strong function of the mass of the system when heritage is held constant (across sizes). Decreasing total mission duration has a strong impact on habitat dry mass below ~300 days, while total habitat mass is primarily driven by spares and consumables (strong dependency on mission duration) above ~300 days. These trends are driven by the transition at 300 days from open-loop Environmental Control and Life Support Systems (ECLSS) to closed-loop ECLSS. That switch decreases the need for consumables at higher mission durations but increases the spares required to maintain those more complicated subsystems.

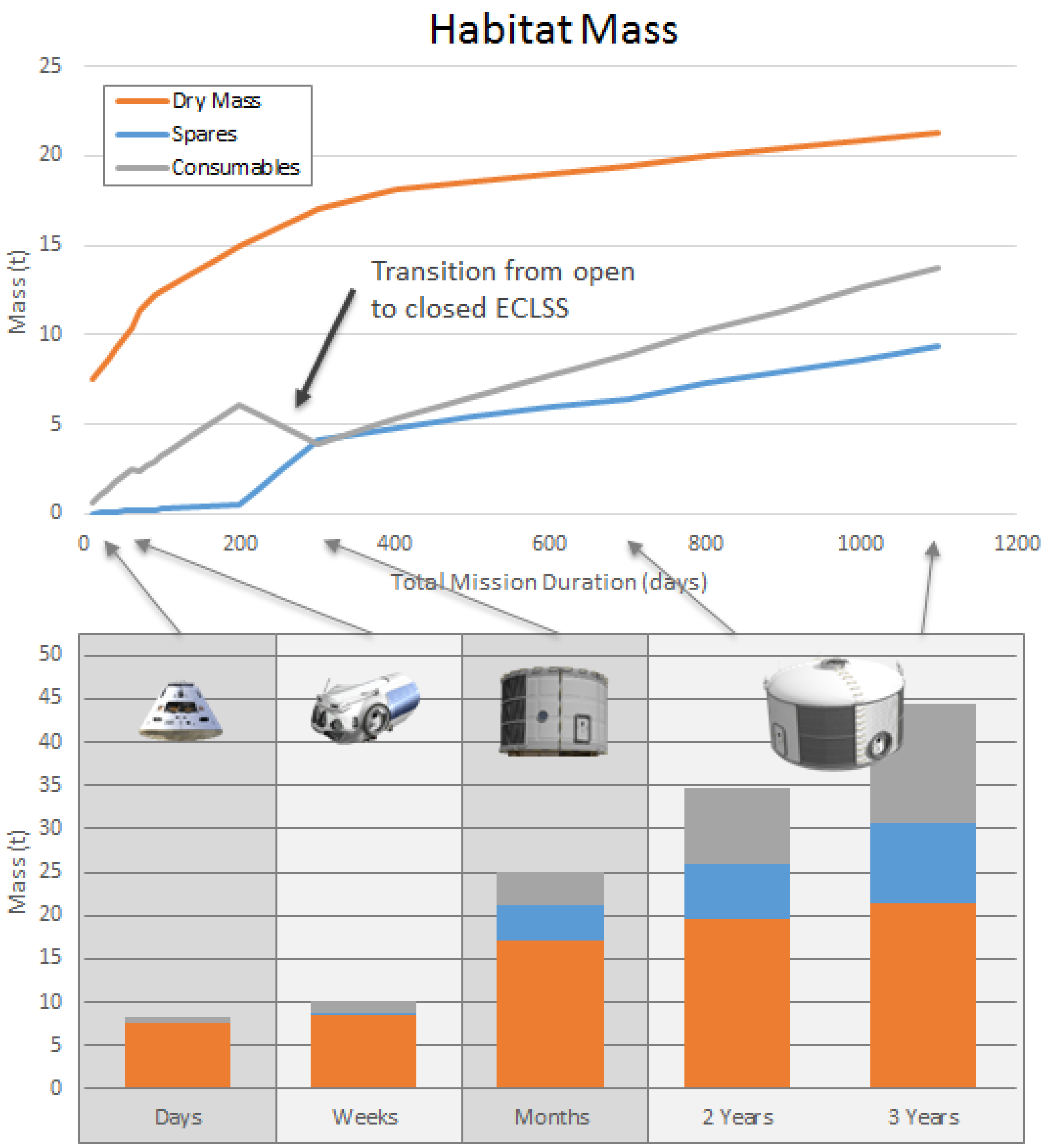

Figure 2: Overview of Habitat Mass and Different Habitat Concepts

In this paper, the habitat and spares costs were estimated using the Project Cost Estimating Capability (PCEC) tool, the results are intended to provide a rough idea of the trend based on the habitat mass and an assumed level of heritage, not a precise estimate. The launch costs (for the habitation systems only) assumed a fixed cost per kilogram to trans-lunar injection (~$24,000/kg). The operations cost are assumed to be constant with mission duration at 50 percent of current ISS operations and maintenance costs.

One limitation of this cost analysis results from the assumption of the habitat lifetime being equal to a single mission duration. For a full understanding of the habitat costs, a full campaign must be considered, including habitat reuse, multiple mission scenarios, and other changes from the baseline orbital mission.

Figure 3 presents the dependency of the non-propulsion system cost on the total mission duration. The difference in the total cost for these four categories between two given mission durations would be available to spend on more advanced transportation systems to achieve the reduced total mission duration. From the figure, cost decreases nearly linearly as total mission duration decreases. Decreasing total mission duration has a weak impact on habitat dry mass, the primary driver for habitat cost, above ~300 days. Below 300 days, the change to open-loop ECLSS, and therefore reduced spares cost, increases the slope of the total cost savings. To give the reader a sense of scale, the total cost without transportation, which includes both development and unit costs, is on the order of $10 billion at high total mission durations.

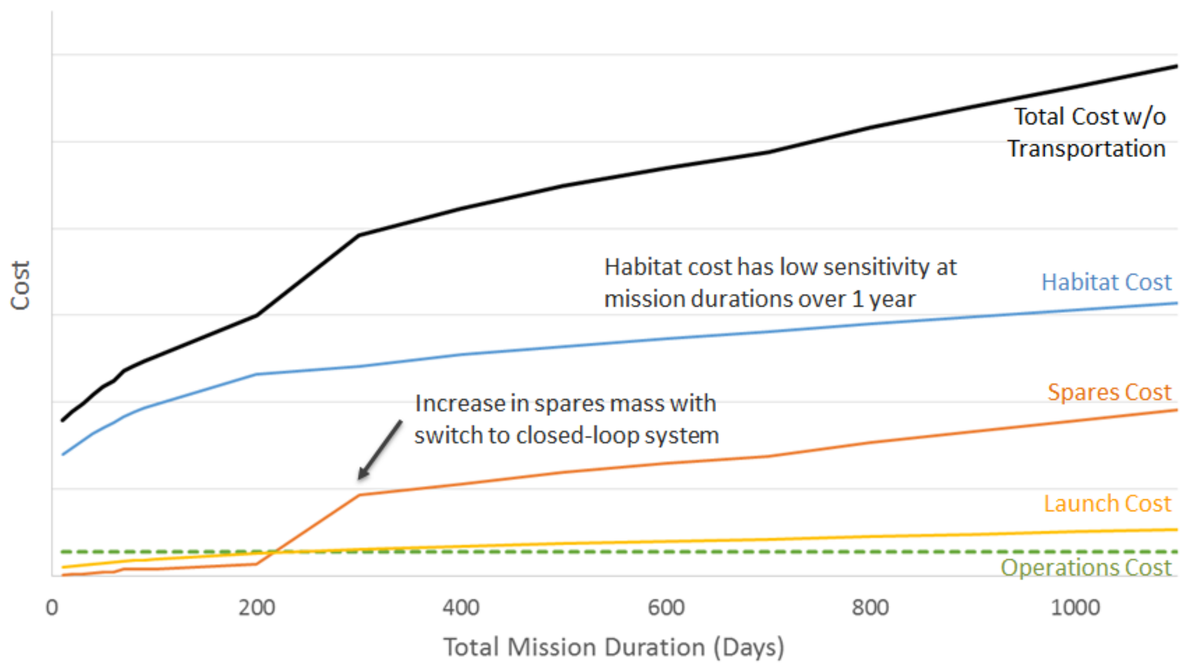

Figure 3: Dependency of Non-Propulsion System Costs on Total Mission Duration

C. Risk

The risk impact determines the chance that the system will fail to achieve its mission, lose the crew, or endanger their long-term health. This impact is comprised of the crew health risks, system reliability, and operational risks. Crew health risks encompass the radiation and microgravity effects on humans during long-duration, deep space missions, and have a significant dependency on the total mission duration. Other mitigation strategies besides reduced mission duration are not incorporated in this study. The system reliability is fixed in this study by varying the spares mass (modeled as a cost driver) as a function of mission duration.. An alternative approach, not considered in this study, is assessing the variation in system reliability for a fixed spares mass.

Finally, the operational risks are typically event-driven and have a weak dependency on total mission duration. Table 3 presents the overview of the risk impact.

Table 3: Overview of the Risk Impact

Component	Description
Crew Health: Radiation	Exposure to deep space radiation poses a health risk to the astronauts during and after the mission; shielding technology and mission duration determine exposure, but policy determines the acceptable level of exposure.
Crew Health: Microgravity	Long term exposure to microgravity has negative impacts on the skeletal, muscular, and cardiovascular systems.
System Reliability	The likelihood that the habitation system will fail before the mission is completed contributes to the mission risk, but this effect is accounted for with spares mass in this analysis.
Operational Risks	Other risks that exist in operation include micrometeoroid and orbital debris, engine burns, launch failure, etc. that are weak functions of mission duration given equivalent concepts of operations.

The radiation portion of the crew health risk has two parts: radiation exposure and the Risk of Exposure Induced Death (REID). The radiation exposure is the amount of radiation that the crew is exposed to during the orbital mission, from both solar radiation and galactic cosmic rays. As shown in Figure 4, exposure is linear with total mission duration. The probability of REID is a combination of the radiation exposure with the impact on the human body, and it may see a superlinear increase with total mission duration. Biological uncertainty also drives error bands on the radiation risk as REID can range from 2-14 percent. For these reasons, the crew health risk due to radiation is likely sensitive to total mission duration, and if that risk is above the acceptable limit (current guidance is 3 percent probability of REID), a shorter total mission duration or other mitigation strategy would be necessary.

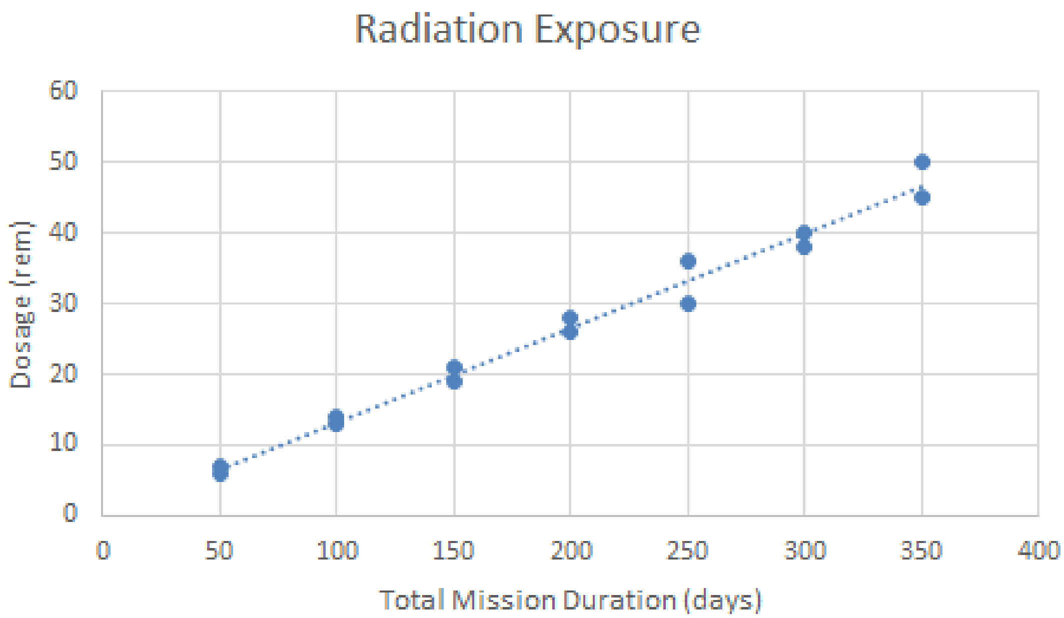

Figure 4: Estimate of Radiation Exposure for Various Mission Durations [Data Source: 4]

There are multiple aspects of crew health risk due to microgravity. Prolonged exposure to a microgravity environment affects a number of the human body's systems, including the skeletal, muscular, and cardiovascular systems. Examples of these impacts include 1.0 to 1.5 percent of bone loss per month, loss of muscle strength & endurance (particularly for lower extremities), and development of kidney stones resulting from bone degradation [5].

It is challenging to model the impacts on the human body due to long duration exposure in deep space. The majority of data on the subject is from experience on Mir and ISS, most of which is for durations of 6 months or less. Currently, exercise is used to mitigate the effects of microgravity on the crew, with ISS crew members exercising 2.5 hours for six out of every seven days. It is still unclear the number of exercise hours required per day for a Mars orbital mission.

There are multiple ways to handle the system reliability risk. Two common strategies are to design to a reliability (used in this analysis) or to design to a cost. When designing to a reliability, the reliability to which the system will be designed is specified, then the required spares mass and component reliability are computed. For the habitats analyzed in this paper, a system reliability of 0.995 is maintained for all mission durations. This converts system reliability from a risk metric to a cost metric. As demonstrated in Figure 5, the risk is driven as much by the uncertainty in the system failure rate as the total mission duration. The analysis performed, based on *Stromgren et al. (2016)*, incorporates the uncertainty in Mean Time Between Failure (MTBF) as seen on ISS to determine the range of spares mass required to maintain a 0.995 habitat system reliability.

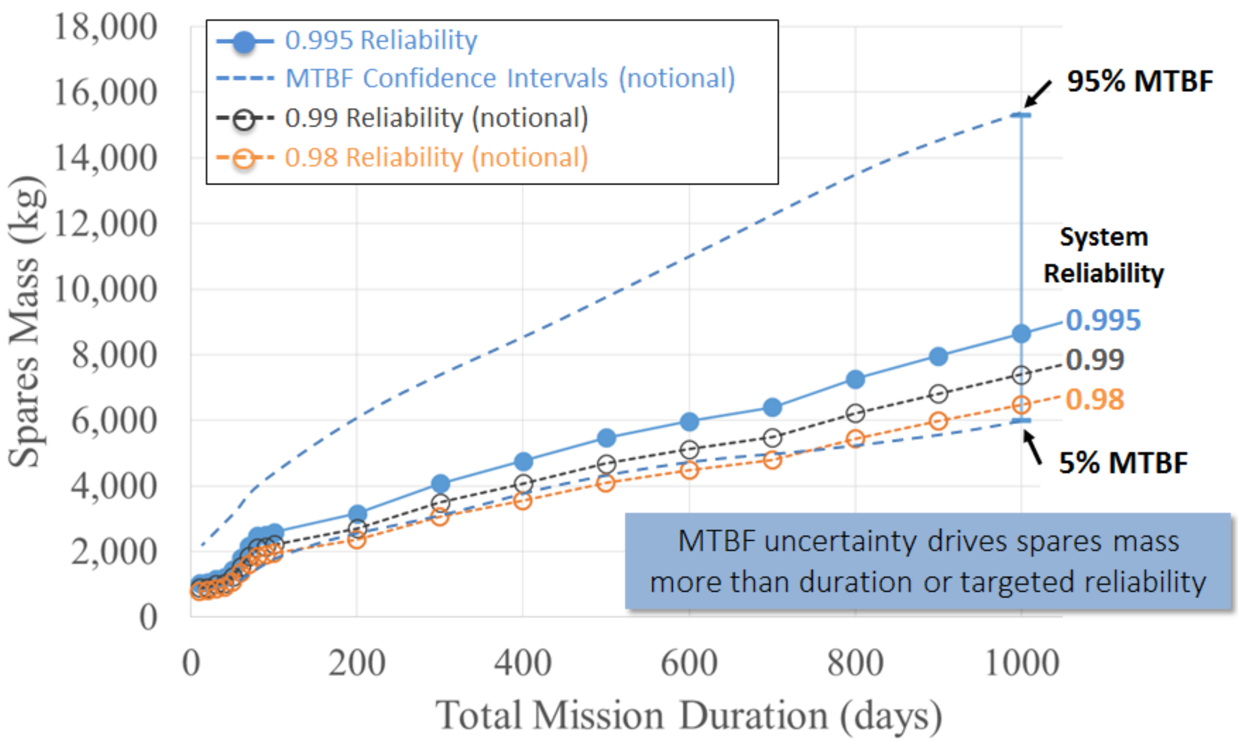

Figure 5: Uncertainty in the System Failure Rate is More Impactful than Total Mission Duration [6]

The other strategy, which was not employed in this study, is to design to a specific cost (equivalent to spares mass and system failure rate). Using this strategy, the failure rate of the elements and the total spares mass available are specified, and then the system reliability falls out as function of operational time. If this approach had been used, risk would have been driven by the total mission duration because the risk increases the longer the system operates. Thus, the impact of total mission duration on system reliability depends in part on the design objective for reliability: whether to design to a fixed reliability (method employed in this study), or to a fixed cost (not considered in this study).

D. Performance

There are several potential approaches for achieving reduced total mission duration. These approaches can be categorized into three categories for the performance trades, as shown in Table 4. Changing the type of trajectory, or mission design, can change the total mission duration and performance requirements on the propulsive vehicle. A change in propulsive technology can achieve shorter mission durations by improving the specific impulse, propellant mass, and, in the case of electric propulsion, power. Changing the propulsion technology has the possibility to dramatically change how a mission is flown, and therefore has a large impact on the total mission duration. Impulsive, high-thrust trajectories have different characteristics from electric, low-thrust propulsion, and converting from one technology to another can alter the very nature of the mission design. Finally, the propulsion concept of operations could change to include propellant resupply, different aggregation strategies, and propellant production at the destination. These concept of operations changes can have dramatic impact on the capability of the transportation system.

Table 4: Overview of the Performance Trade Options

Component	Description
Mission Design	Change the type of trajectory to change the mission duration and the performance requirements, includes constant thrust vs. impulsive thrust trade
Propulsion Technology	Change the characteristics of the vehicle to achieve the performance requirements (e.g. changing propulsion technology to increase specific impulse).
Operational	Change the concept of operations to include options such as propellant refueling, aggregation and/or pre-deploy, ISRU, etc.

To understand how the performance trades impact the total mission duration, Figure 6 presents representative missions from four mission classes: total mission durations of years, months, weeks, and days. The "Years" mission class is comparable to the missions that have been designed for previous Mars architectures [7,8] where orbital mechanics dictate long stay times and interplanetary Times of Flight (TOF) above 100 days. Reductions in time of flight for this mission class has limited impact on the total mission duration because the orbital mechanics dictate that the stay time increase. The "Months" mission class has significant variety, but the mission shown has a very short stay time and transits off of the optimal return date. The performance, denoted by total change in velocity, or ΔV, is an order of magnitude greater for the "Months" mission class over the "Years" mission class. Trajectories in the "Years" mission class use current transportation technologies, and those of the "Months" mission class would require significant technological advancement. "Weeks" and "Days" mission classes would require a physics breakthrough to achieve those types of mission durations which have extremely high performance requirements.

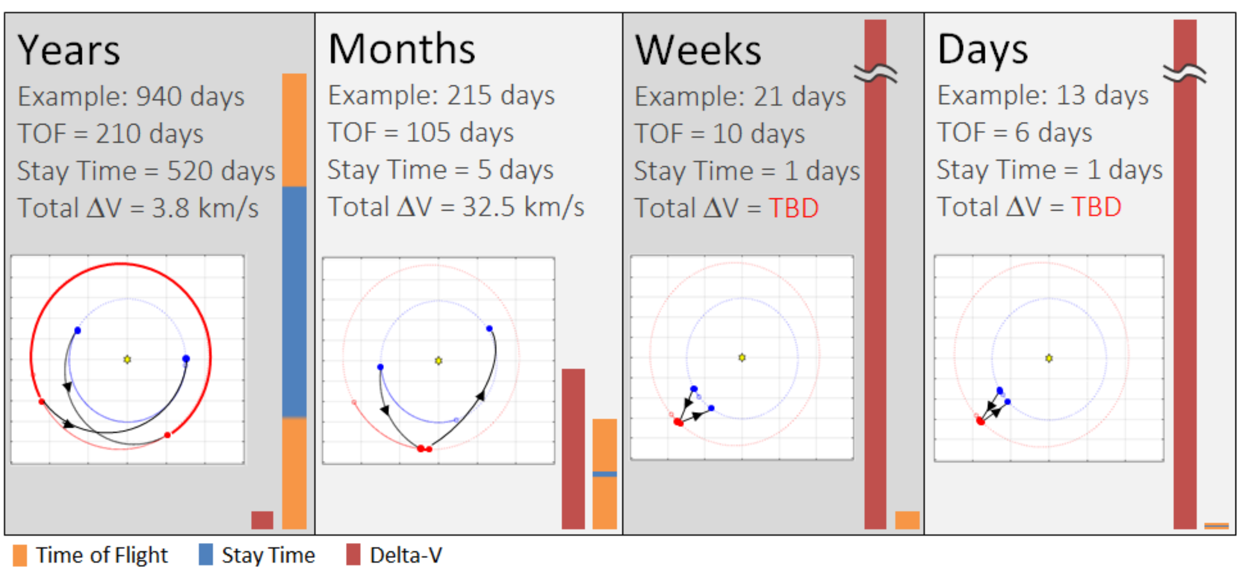

Figure 6: Comparison of Trajectories with Different Total Mission Duration Classes

Figure 7 presents a case study using inert mass fraction sizing to determine the increase in performance (specific impulse and mass ratio) needed to achieve a reduced TOF. The baseline, Minimum ΔV, case has a total mission duration of 940 days and times of flight of 210 days each way. The performance required to depart cislunar space is achievable with conventional or near-term propulsion technologies--LOX/CH4, LOX/LH2, and Nuclear Thermal Rockets (NTR)--at reasonable initial masses. However, decreasing the times of flight by 50 percent only decreases the total mission duration by 7 percent. At the same time, that trajectory would only be achievable with NTR, the best performing and least developed of those propulsion technologies, which would still require six Space Launch System launches of flight hardware and propellant. The takeaway from this case study is that increases in specific impulse and mass ratio only enable small reductions in total mission duration.

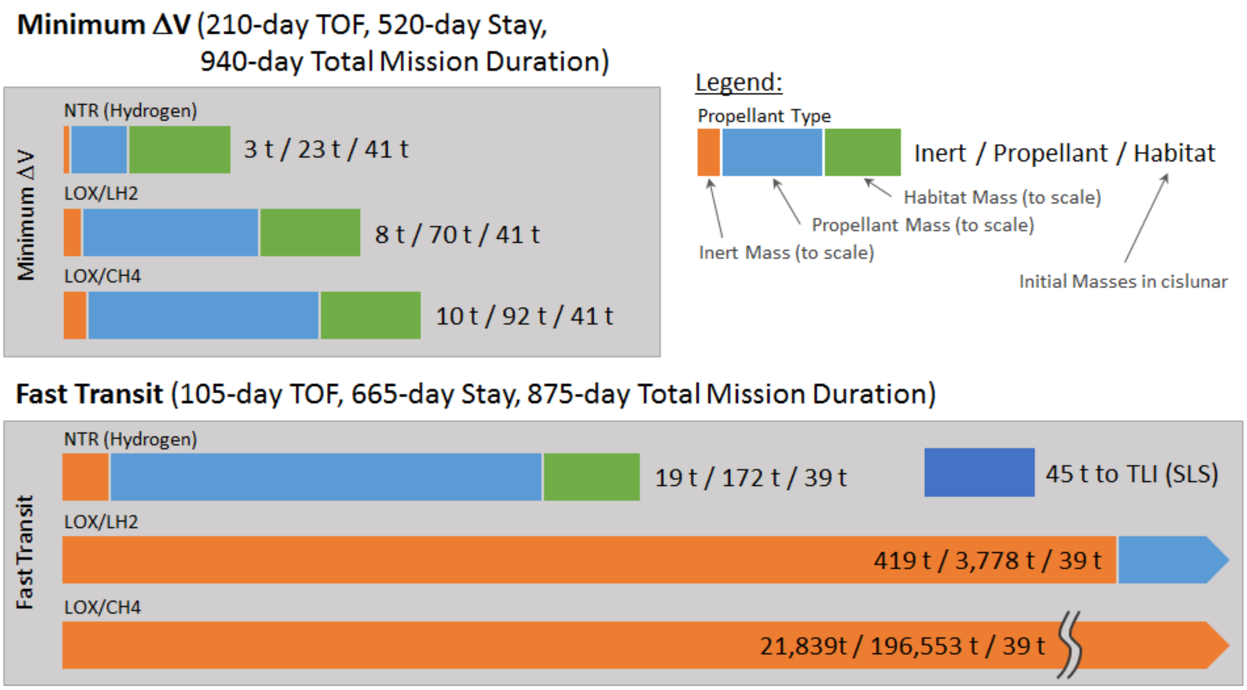

Figure 7: Case Study of Decreasing Time of Flight for Impulsive Trajectories

Technologies are being researched that would enable significant decreases in trip time, including the VASIMR engine [4]. Table 5 presents the needed performance from this engine concept to achieve total mission durations below one year (would fall in the "Months" mission class). Mission durations under one year would require orders of magnitude improvement in power and specific power. Total mission durations of weeks or days would require a physics breakthrough (e.g. propellantless propulsion).

Table 5: Needed Performance for Mission Durations Less Than One Year

	Current Performance	Needed Performance
Isp (s)	~3,000[a]	~5,000[c]
Power (MW)	0.01[b]	10 - 100[c]
Specific Power (kg/kW)	150[b]	1 - 10[c]

[a]HERMeS Thruster, [b]Kilo-Power Nuclear Reactor Concept, [c]VASIMR

IV. Key Findings and Discussion

For the Mars orbital mission, reducing total mission duration potentially has the greatest impact on risk, primarily crew health risk, but risk impacts have large uncertainty. Long duration, deep space missions may exceed the current limits on radiation exposure, and risk uncertainty is driven by biological uncertainty, which can dominate the difference in risk due to mission duration. System failure risk is mitigated by increasing spares mass, while crew health risk mitigation strategies beyond reduced mission duration have not been explored in this paper. Reducing total mission duration also decreases habitat cost, but this reduction is dominated by the increased transportation system cost (via the mass). Finally, the change in benefit associated with reducing total mission duration is negligible.

Reductions in total mission duration can be achieved by a continuum of operational and technological solutions: mission design, increasingly efficient propulsion, and physics breakthroughs. Figure 8 presents this continuum and the types of mission classes it enables. Changes in mission design can reduce total mission duration while utilizing the same type of propulsion technology. Achieving missions below two years in duration require more efficient propulsion technology, while achieving missions under one year duration requires orders of magnitude improvement in technology and/or a physics breakthrough, such as propellantless propulsion.

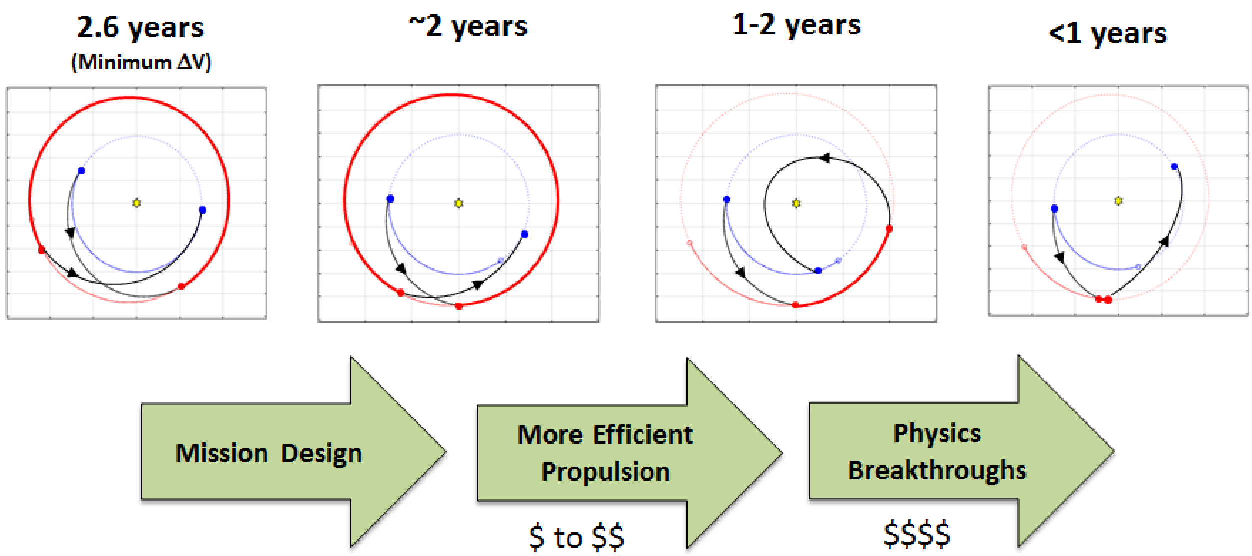

Figure 8: The Continuum of Performance Solutions to Decrease Total Mission Duration

Figure 9 presents the behavior of habitat cost, notional propulsion cost, and crew health risk to show a knee in the curve of total cost vs. total mission duration (and therefore risk). The habitation system cost decreases with mission duration, but the propulsion system, based on the mass at departure for Mars, will increase exponentially in cost as total mission duration decreases. Combining the transportation and habitation costs shows a knee in the curve where more reductions in mission duration for a given propulsion technology would increase cost rapidly. A further decrease in mission duration can be realized by changing propulsion technology, which would have a knee in the curve at lower total mission duration. It is important to note that the propulsion cost curves are notional, and therefore the location of the knee in the curve is only representative of how to interpret the behavior of the plot.

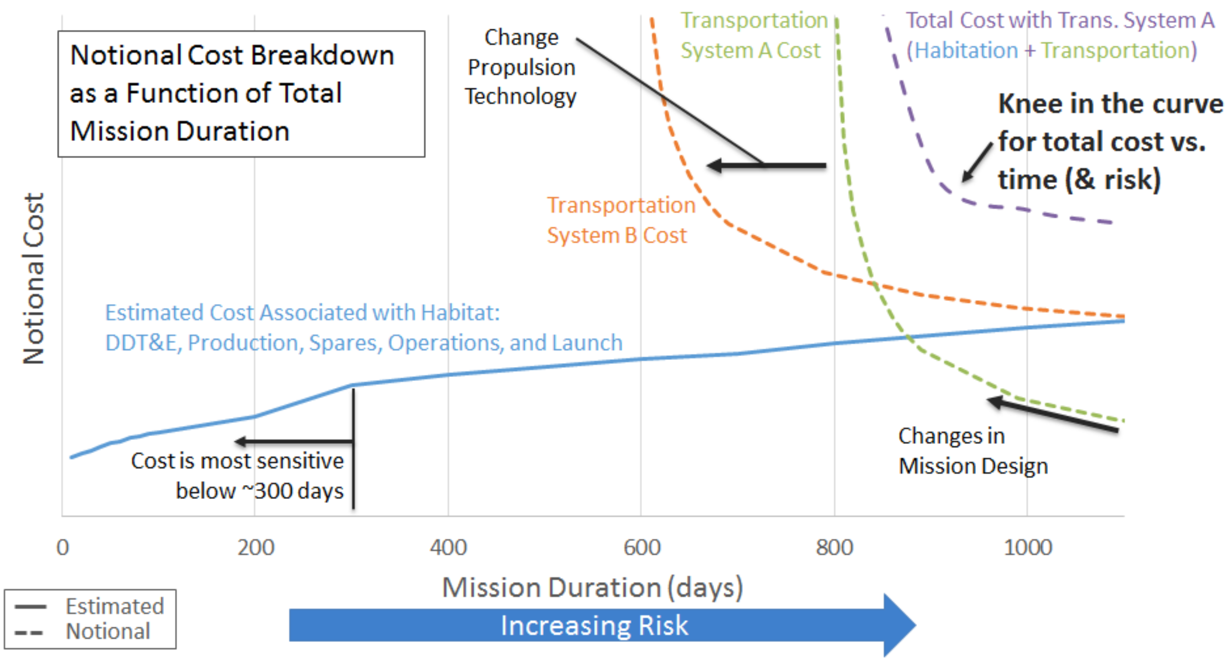

Figure 9: Notional Cost of Transportation and Habitation as a Function of Total Mission Duration

V. Conclusions

This paper assessed the sensitivity of the total impact of reducing the total mission duration of a human Mars orbital mission, including benefit, cost, and risk. Reductions in total mission duration can be achieved by a continuum of operational and technological solutions: alter the mission design, utilize increasingly efficient propulsion, and the potential for physics breakthroughs. The key findings from this assessment reveal that reducing total mission duration potentially has the greatest impact on risk, which is driven by the mitigation of crew health risks (e.g. exposure to radiation and microgravity). Risk impacts have large uncertainty, and more research would be necessary to better understand and model these risks. The reduction in non-transportation (e.g. habitation) systems' cost resulting from reduced total mission duration are most sensitive below ~300 days, but those cost savings are dominated by the increased in-space transportation cost to go faster. Finally, for a Mars orbital mission, the change in benefit associated with reducing total mission duration is negligible.

To see meaningful changes in these impacts for the orbital mission, the total mission duration must be reduced dramatically, potentially below a one year round-trip. Performance requirements increase exponentially for decreased total mission duration in those time scales, often requiring orders of magnitude improvement in propulsion technology.

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